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Discovery of a $z = 6.1$ Radio-Loud Quasar in the NDWFS

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ABSTRACT

From examination of only 4 deg^2 of sky in the NOAO Deep Wide-Field Survey (NDWFS) region, we have identified the first radio-loud quasar at a redshift $z > 6$. The object, FIRST J1427385+331241, was discovered by matching the FLAMEX IR survey to FIRST survey radio sources with NDWFS counterparts. One candidate $z > 6$ quasar was found, and spectroscopy with the Keck II telescope confirmed its identification, yielding a redshift $z = 6.12$. The object is a Broad Absorption Line (BAL) quasar with an optical luminosity of $M_B \sim -26.9$ and a radio-to-optical flux ratio ~ 60. Two Mg II absorptions systems are present at redshifts of $z = 2.18$ and $z = 2.20$. We briefly discuss the implications of this discovery for the high-redshift quasar population.

1. Introduction

High-redshift quasars provide both interesting constraints on the growth of the first supermassive black holes, and light sources with which to probe the ionization history of the Universe. The Sloan Digital Sky Survey (SDSS) broke the $z = 6$ barrier after covering its first 1550 deg^2 (Fan et al. 2001) and has subsequently identified a total of nine objects with $z \geq 6$ drawn from sky coverage of 6550 deg^2 (Fan et al. 2001, 2003, 2004, 2006). Owing to the relatively bright limiting z'-band magnitude of the SDSS survey, all of these quasars are luminous, with $M_B < -26.5$. Fan et al. (2004) derive estimates for the space density ($6 \pm 2 \times 10^{-10}$ Mpc^{-3} for $M_{1450} < -26.7$) and luminosity function using nine SDSS-discovered quasars with $z > 5.7$, concluding $\Psi(L) \sim L^{-3.2 \pm 0.7}$. This steep luminosity function suggests deeper surveys could locate large numbers of high-redshift objects.

All of the $z > 6$ quasars discovered to date are radio-quiet, with ratios of radio to optical flux < 10. One source has been detected at 20 cm with a flux density of 55μJy,

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while a second has a measured value of 26 ± 12 μJy (Carilli et al. 2004). The most distant quasar known with a flux density level of > 1 mJy is SDSS J083643.85+005453.3 at $z = 5.82$. However, based on semi-analytic models of dark halo formation, Haiman et al. (2004) predict high surface densities of high-redshift radio-loud quasars; in particular, they suggest roughly four $z > 6$ quasars per square degree should be found in the catalog constructed from Faint Images of the Radio Sky at Twenty-cm (FIRST – Becker et al. 1995). Motivated by this suggestion, we have matched the FIRST catalog to the NOAO Deep Wide-Field Survey (NDWFS – Jannuzi & Dey 1999) and the recently released FLAMINGOS EXtragalactic Survey (FLAMEX – Elston et al. 2006), yielding a net survey area of 4.1 deg^2. The result is the detection of the first $z > 6$ radio-loud quasar.

In Section 2, we briefly describe the catalogs used for this project. We then go on to present our search procedure which produced one good candidate object (§3). Section 4 describes the spectroscopic confirmation of this quasar, §5 its continuum properties from rest UV to IR, and §6 its absorption line systems. In §7 we discuss the implication of this discovery for the high-redshift quasar population as well as for future searches for high-redshift objects. Magnitudes are reported in the Vega system unless otherwise noted. Photometry in the optical to near-infrared was obtained from SExtractor (Bertin & Arnouts 1996) MAG_AUTO magnitudes. Throughout the paper we use the standard cosmological model, with parameters $\Omega_\lambda = 0.7$, $\Omega_M = 0.3$, and $H_0 = 70$ km s^{-1} Mpc^{-1} (Spergel et al. 2003).

2. Survey Data

2.1. NDWFS

Beginning in 1999, the NDWFS (Jannuzi & Dey 1999) obtained deep ($R \sim 26$) images in three optical bands (B_w, R, and I) over two 9 deg^2 fields with the MOSAIC imager on the Mayall 4-m telescope. The Survey's Third Data Release[1] includes calibrated images and source catalogs for the northern (Boötes) field. Separate catalogs were derived for each band using SExtractor; a merged catalog was also produced which includes the three optical bands along with partial coverage in the K band.

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[1] $http://www.noao.edu/noao/noaodeep/DR3/dr3-descr.html$

2.2. FIRST

We produced the FIRST survey (Becker et al. 1995) from data collected between 1993 and 2004 using the Very Large Array[2] in its B configuration operating at 20 cm. Over 9000 deg^2 of the Sloan Digital Sky Survey footprint was imaged to a sensitivity of 1 mJy, with astrometric accuracy better than 1″; all images and catalogs are available at the FIRST website[3]. The radio source surface density is ~ 90 deg^{-2}; 906 sources fall within the NDWFS Boötes field.

2.3. FLAMEX

The FLAMEX Survey (Elston et al. 2006) is the largest survey available in the near-IR to $K \sim 20$. It was conducted on the KPNO 2.1-m telescope between 2001 and 2004, ultimately covering 4.7 deg^2 of the Boötes region; the net overlap with NDWFS is 4.1 deg^2. The survey is 50% complete at $K_s = 19.5$; the stated limit at J is ~ 21.4. A catalog of $\sim 157,000$ K_s-selected sources was produced using SExtractor and was released through the FLAMEX website[4].

3. Candidate Selection

In order to identify high-redshift quasar candidates, we searched the NDWFS Boötes survey region for compact FIRST sources, defined as having a fitted semi-major axis of less than 2.5″. There are 394 FIRST sources meeting this criterion in the NDWFS field, of which 168 lie in the intersection of the NDWFS and FLAMEX survey regions. Roughly 60% of the FIRST sources can be identified with NDWFS counterparts; this fraction increases to $\sim$ 75% when FLAMEX is included.

The photometric redshift code `hyperz` of Bolzonella et al. (2000) was used to estimate redshifts for the entire sample of optical/IR radio-source counterparts. The composite radio-emitting quasar spectral template from the FIRST Bright Quasar Survey (FBQS, Brotherton et al. 2001) was used to fit the optical/IR photometry. This template was treated as a

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[2]The VLA is a facility of the National Radio Astronomy Observatory which is operated by Associated Universities, Inc. under cooperative agreement with the National Science Foundation.

[3]*http://sundog.stsci.edu*

[4]*http://flamingos.astro.ufl.edu/extragalactic/data.html*

non-evolving model characteristic of radio-loud and radio-intermediate quasars. We fit the template to the NDWFS and FLAMEX photometry over a range of redshifts $0 < z < 10$, and included intrinsic dust absorption as a parameter, using the starburst galaxy dust model of Calzetti et al. (2000). The `hyperz` code also includes Lyman forest absorption according to the model of Madau (1995).

A set of four candidate $z > 4$ radio-loud quasars from the best-fit `hyperz` redshift estimates was then examined by eye, using the optical images from NDWFS; two of these had putative redshifts greater than six. Only the source FIRST J1427385+331241 ($F_{peak} =$ 1.7mJy) had all of the expected properties of a bright $z > 6$ quasar: no emission in the B_w and R bands, detection in the I band with a high stellarity ($I = 22.1$, SExtractor CLASS_STAR = 0.98), and relatively bright infrared fluxes ($J = 18.7$, $K_s = 17.4$). The offsets between the optical, infrared, and radio positions are small ($\lesssim 0.3''$) and consistent with astrometric uncertainties. The source was thus selected as the prime candidate for spectroscopic follow-up observations.

4. Observations

A discovery spectrum was obtained as the source was rising at dawn on 2006 January 3 at the Keck II telescope using the ESI spectrograph ($R \sim 4000$). This spectrum was sufficient to identify the source as a $z = 6.12$ quasar; however, the seeing was bad and the source was at a high airmass, so the S/N was poor. A higher S/N spectrum was obtained at Keck II on March 5, again using the ESI (Figure 1). The total exposure time was 40 minutes under good conditions, with seeing of $0''.8$.

FIRST J1427385+331241 was observed in J and K_s at the MDM observatory 2.4-m Hiltner telescope using TIFKAM[5] on 2006 April 12 and 15 under non-photometric conditions. For both bands, SExtractor was used to detect and measure sources in the $4' \times 4'$ field. Calibration was performed using 2MASS stars within the field. The quasar was just detected ($S/N \sim 2$) in the J band in a 20 minute integration, with a Vega magnitude $J = 19.9 \pm 0.5$. A 28 minute integration in the K_s band also detected the quasar ($S/N \sim 4$) with a magnitude $K_s = 17.93 \pm 0.25$. The discrepancy between the MDM and FLAMEX measurements was resolved by examining the FLAMEX images (S. A. Stanford, private communication), where it became evident that flux from a nearby source ($3''$ west) was blended with the quasar's

[5]TIFKAM was funded by Ohio State University, the MDM consortium, MIT, and NSF grant AST 96-05012. NOAO and USNO paid for the development of the ALADDIN arrays and contributed the array currently in use in TIFKAM.

flux. The standard IRAF DAOPHOT routines were used to construct PSFs from the images and to fit simultaneously the quasar and the nearby source. From this process, we obtained $J = 19.68 \pm 0.05$ and $K_s = 17.88 \pm 0.16$ from the FLAMEX images, in good agreement with the MDM observations. All photometric observations of FIRST J1427385+331241 are shown in Table 1.

The VLA European Large-Area ISO Survey (ELAIS – Ciliegi et al. 1999) detected this source as ELAISR142738+331242, and reported a 1.4 GHz flux density of 1.816 ± 0.021 mJy, compared to the 1.73 ± 0.13 mJy flux density from FIRST. The source is also barely visible in the NRAO VLA Sky Survey (NVSS – Condon et al. 1998) image of this region, where it is merged with a brighter nearby source; the sum of the flux densities of the two resolved sources from FIRST is consistent with the reported NVSS flux density. Thus, there is no evidence of large variations at radio wavelengths.

The source is not detected in the Chandra XBootes survey (Murray et al. 2005), implying an upper limit in the 0.5-7 keV band of 4×10^{-15} erg cm^{-2} s^{-1}. Using the Galactic N_H at this location of 1.1×10^{20} cm^{-2} and a power law slope of $\Gamma = 1.9$ yields a rest frame luminosity upper limit $L(3.5 - 14 \text{ keV}) < 1.0 \times 10^{45}$ erg s^{-1}, only a factor of $2 - 3$ below the X-ray luminosities detected for other high-redshift (albeit, radio-quiet) quasars (Brandt et al. 2002). The evidence, presented below, that this object is a BAL could explain its modest observed X-ray flux, since intrinsic column densities of up to 4×10^{23} cm^{-2} have been seen in such objects (Gallagher et al. 2002); in this case the luminosity upper limit increases by $\sim 50\%$.

We obtained Spitzer IRAC archival images of the Boötes field, from a survey conducted by Eisenhardt et al. (2004). The source is detected in all four IRAC bands. Measured fluxes from analyzing the Post-BCD images with SExtractor are $68 \pm 7\mu$Jy at 3.6μm, $77 \pm 7\mu$Jy at 4.5μm, $93 \pm 8\mu$Jy at 5.8μm, and $72 \pm 7\mu$Jy at 8.0μm. The Boötes field has also been surveyed at 24μm by Houck et al. (2005). A catalog is not yet available, but examination of archival images reveals a possible detection of the source, based on a small fluctuation ($\sim 1.7\sigma$) in the image at the quasar position. We adopt a rough upper limit of 0.2mJy for the 24μm flux of this source. These mid-infrared fluxes are comparable to measurements of SDSS $z > 5.8$ quasars from the Spitzer survey conducted by Jiang et al. (2006). From the 24μm upper limit we see no evidence for a hot dust mass (see Figure 2) as was found for 11 out of 13 of the quasars observed by Jiang et al. (see their Figure 3). The ratio of rest-frame near-IR to optical luminosities for FIRST J1427385+331241 is also low, $\log(\nu L_\nu[3.5\mu\text{m}]/\nu L_\nu[4400\text{Å}]) \lesssim -0.4$. Jiang et al. compare the two quasars in their sample showing similarly weak NIR fluxes to low redshift samples and find that such cases are very rare; they suggest that dust evolution at high redshift may explain why a significant fraction ($\sim 20\%$) of $z \sim 6$ quasars are NIR-weak.

5. Continuum Properties

In Figure 2, we show the full optical to infrared spectral energy distribution (SED) of FIRST J1427385+331241. The SED does not resemble a simple power law, and the large flux ratio between the rest-frame ultraviolet and optical range suggests that dust extinction may be responsible for the observed optical and near-infrared colors ($I - J = 2.4$ and $J - K = 1.8$). We derive the rest-frame luminosity of the quasar by fitting the redshifted FBQS template to the IRAC measurements, which are the least affected by dust. From this process we derive $M_B = -26.9$ and $M_{1450} = -26.4$; only one known $z > 6$ quasar is less luminous: SDSS J1630+4012 has $M_{1450} = -26.1$ (Fan et al. 2003). Using a template to derive UV/optical luminosities ignores dust reddening; the flux levels in our Keck spectrum at these wavelengths are much lower, most likely as a consequence of slit losses which render these data unreliable for deriving magnitudes. As none of the $z \sim 6$ SDSS quasars have shown significant dust extinction, using the template to derive luminosities allows a direct comparison to that sample.

In order to compare the radio and optical properties of FIRST J1427385+331241, we adopt the definition of radio loudness from Ivezić et al. (2002), $R_m = 0.4(m - t)$, where m is an optical AB magnitude and t is the "AB radio magnitude" at 1.4 GHz. This definition does not include a K-correction, and thus probes different regions of the spectral energy distribution at different redshifts. We consider two regions based on observations of $z > 6$ sources. At $z \sim 6$, the B band is redshifted to the near-infrared ($\sim 3\mu m$), such that a comparison of the flux at 1.4 GHz to the IRAC 3.6μm flux is an approximation to the usual definition of radio loudness in terms of the ratio of 5 GHz radio to B-band optical flux (Kellerman et al. 1989). Using an AB magnitude of 19.32 at 3.6μm, the radio loudness for FIRST J1427385+331241 is $R_{3.6\mu\mathrm{m}} = 1.4$. We also consider the radio-loudness for $z > 6$ sources in terms of the rest-frame ultraviolet; specifically, to compare with the SDSS quasars, we use the flux at 1450Å. Using the values of m_{1450} obtained from template fitting as described above, the radio-loudness of the quasar is $R_{1450} = 1.8$. The quasar SDSS J1148+5251 detected by Carilli et al. (2004) with a flux density at 1.4 GHz of 55μJy has $R_{1450} = -0.2$ and $R_{3.6\mu\mathrm{m}} = -0.4$, so FIRST J1427385+331241 is truly the first $z > 6$ radio-loud quasar.

FIRST J1427385+331241 is a Broad Absorption Line Quasar (BALQSO), as is evident from the strong absorption features blueward of the N V and Si IV emission lines (see Figure 1). BALQSOs are more intrinsically reddened than non-BALQSOs (Trump et al.

2006; Reichard et al. 2003; Brotherton et al. 2001). Figure 2 shows that a simple model using a power law with slope $\alpha = -0.5$ reddened by a Small Magellanic Cloud (SMC, Prevot et al. 1984; Pei 1992) dust model with $E(B-V) = 0.1$ gives a good fit to the observed SED. This dust model agrees with the FBQS sample of low-redshift BALQSOs (Brotherton et al. 2001), where the spectral shape of the low-ionization BALQSO composite was consistent with the non-BALQSO composite reddened by SMC dust with $E(B-V) \sim 0.1$. SDSS J1048+4637, at $z = 6.2$, is also a BALQSO; thus the BAL fraction for known $z > 6$ quasars is $\sim 20\%$, similar to the low-redshift fraction ($\sim 10 - 15\%$, Trump et al. 2006; Reichard et al. 2003; Weymann et al. 1991).

6. Mg II absorption

The high-S/N Keck spectrum reveals two strong Mg II $\lambda\lambda 2796, 2803$ absorption systems (Figure 3). The first is at observed wavelengths 8894Å and 8916Å, giving an absorber redshift of $z = 2.1804 \pm 0.0003$. The second shows both the Mg II doublet and the Mg I $\lambda 2852$ line, at observed wavelengths 8948Å, 8970Å, and 9128Å respectively, yielding an absorber at $z = 2.1997 \pm 0.0002$. The velocity separation of these systems is ~ 5800 km/s; they are unlikely to be part of a single cluster but may be associated with large-scale structure.

The presence of absorption systems in the line-of-sight raises the possibility that the quasar is being gravitationally lensed. By examining quasars in the 2dF survey, Ménard & Péroux (2003) found evidence for gravitational magnification of sources with strong Mg II/Fe II absorbers. Murphy & Liske (2004) also detected magnification of SDSS quasars with intervening DLAs. Ménard & Péroux (2003) discuss how the absorption systems are responsible for competing effects: while the overall brightness of the source is increased by gravitational lensing, extinction effects in the absorber's frame will redden the source. Murphy & Liske (2004) did not find evidence for systematic reddening of SDSS quasars by DLAs at $z_{abs} \sim 3$, but York et al. (2006) did find reddening as large as $E(B-V) \sim 0.1$ in SDSS quasars with Mg II absorbers in the interval $1.0 < z_{abs} < 1.86$. For a single source, especially a BALQSO which is likely to be intrinsically reddened, it is impossible to tell whether either of these two effects are present; we simply note that both the inferred luminosity and the spectral shape of FIRST J1427385+331241 may be affected by the two Mg II absorbers.

7. Discussion

Approximately 10% of the normal SDSS quasars are detected in the FIRST survey (White et al. 2006). The fact that SDSS has found one $z > 6$ quasar (all radio quiet) per ~ 730 deg^2 searched and we have found a radio-loud object in a 4 deg^2 survey requires examination,[6] as a naive estimate would predict our chances of success to be 4.1 deg^2/730 deg^2 $\times$ $0.1 = 6\times10^{-4}$. Allowing for the possibility that the quasar is being gravitationally magnified, we might have reached ~ 1 mag deeper into the quasar luminosity function than Fan et al. Even with a steep luminosity function $\Psi(L) \sim L^{-3.2}$, this would only increase the number density by a factor of ~ 20; the number density of 6×10^{-10} Mpc^{-3} from Fan et al. (2004) would predict ~ 0.1 quasars in 4 deg^2 in the redshift range $6 < z < 7$, such that, including the radio-loud fraction, our chances would have been $\lesssim 1$%.

In addition to the predictions of high surface densities of radio-loud quasars put forth by Haiman et al. (2004), we expected that the use of deep optical and infrared surveys would allow us to reach less luminous quasars at high redshifts. Figure 4 shows that the combination of NDWFS and FLAMEX should probe much deeper into the luminosity function of high-z quasars than the corresponding search conducted using the SDSS. We thus expected to find, if anything, a quasar too faint to fall within the SDSS program limits and identified by the combination of deep optical/IR imaging with radio selection.

This quasar is just below the reach of the SDSS program, as shown in Figure 4. The NDWFS I band, which essentially covers the combined wavelength range of the SDSS i' and z' bands, easily detected this source, as did the FLAMEX J. Thus we did not fully utilize the deep coverage of the Boötes region surveys in locating this particular source. In addition, while radio detection was the primary criterion for our quasar search, it was not essential in this case, as the quasar could have been identified by its optical and infrared properties alone (as an R-band dropout); however, the use of radio detection does eliminate contamination from L and T dwarf stars. This quasar is not particularly underluminous relative to other $z > 5.8$ quasars (see Figure 4); it is the object's red optical colors that prevented it from being detected by SDSS. As at low-redshift, radio selection has located quasars that are redder than those found by optical criteria (White et al. 2003). The improbable discovery of this quasar suggests that dust obscuration may be important at high redshift, and that current estimates for the quasar number density at $z \sim 6$ are too low. Radio searches such as this one, and mid- to far-IR searches such as that of Cool et al. (2006) are likely to find a new population of sources at high redshift.

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[6]One possible explanation is that we are, as previously documented, just lucky (Becker, Helfand, and White 1992; White, Kinney, and Becker 1993; Stern et al. 2005).

The issue of the redshift dependence of quasar radio emission has been debated in the literature for decades. The consensus ten years ago appeared to be that "the fraction of radio-loud quasars decreases with increasing redshift" (Schmidt et al. 1995 and references therein). From observations of forty optically selected quasars with $3.3 < z < 4.9$ (including all quasars then known with $z > 3.9$) Schmidt et al. detected three objects at a 20 cm flux density threshold of 0.2 mJy, far below their expectation of 9-18 detections. However, all such studies relied on rather small and heterogenous samples of objects with different selection criteria. Recently, we have studied the radio properties of the 41,295 quasars from the SDSS DR3 catalog that fall within the FIRST survey area (White et al. 2006). An important feature of our analysis is that we include *all* quasars – especially the $\sim 90\%$ which fall below the radio detection threshold – by stacking the radio images.

White et al. (2006) find a very tight correlation of radio luminosity with absolute magnitude at all redshifts, but, importantly, the slope of the relation is not unity: $L_R \sim L_{opt}^{0.72}$. Thus, the higher luminosity optical objects – inevitably those found in magnitude-limited high-z surveys – are underluminous in the radio when compared with the mean of the lower-redshift population. When normalized for this dependence on optical luminosity, we find a remarkably flat distribution of the radio-to-optical flux ratio R for quasars with redshift: the mean value of R changes by less than 0.1 from $z = 0$ to $z = 5$ (White et al. 2006, figure 11; see also Cirasuolo et al. 2006 and Petric et al. 2003). The cumulative fraction of quasars above the Schmidt et al. (1995) limit of 0.2 mJy at 6 cm is ~ 0.12 in our SDSS sample (assuming a radio spectral slope of $\alpha = -0.5$ between 20 and 6 cm). Correcting for the (high) mean optical luminosity of the Schmidt et al. sample ($M_B = -26.3$) reduces the expected fraction by 20% to 0.10. Thus, we would expect four detections in their sample of forty; three objects were detected. We conclude that the expectation of discovering a radio-loud quasar at high z is not reduced significantly by a decline in radio emission with redshift; indeed, the fact that two of nineteen quasars now known above $z = 5.7$ lie above the FIRST survey threshold is not unexpected.

Our discovery of a $z > 6$ radio-loud quasar in a 4-deg^2 survey suggests that tractable wider-area surveys with deep K-magnitude (and deeper radio) limits would be highly productive. We have not yet exhausted the possibilities in the FLAMEX region, as the ~ 200 radio sources showing extended emission have yet to be matched. The detection of more, higher-z objects could provide useful probes of the epoch of reionization through redshifted 21 cm absorption measurements.

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Table 1. Photometric Observations of FIRST J1427385+331241

Survey	Band	mag	error	flux density (mJy)
NDWFS	B_w	>26.4	···	
	R	>25.5	···	
	I	22.09	0.02	
FLAMEX	J	19.68	0.05	
	K_s	17.88	0.16	
MDM	J	19.93	0.50	
	K_s	17.92	0.24	
IRAC	3.6μm	16.53	0.11	0.068
	4.5μm	15.91	0.10	0.077
	5.8μm	15.24	0.09	0.093
	8.0μm	14.86	0.11	0.072
MIPS	24μm			<0.20
FIRST	20 cm			1.73

Note. — All magnitudes are in the Vega system. NDWFS, MDM, and IRAC magnitudes were all obtained from SExtractor MAG_AUTO. FLAMEX magnitudes are not taken from the catalog, but from PSF fitting using IRAF DAOPHOT (see Section 4).

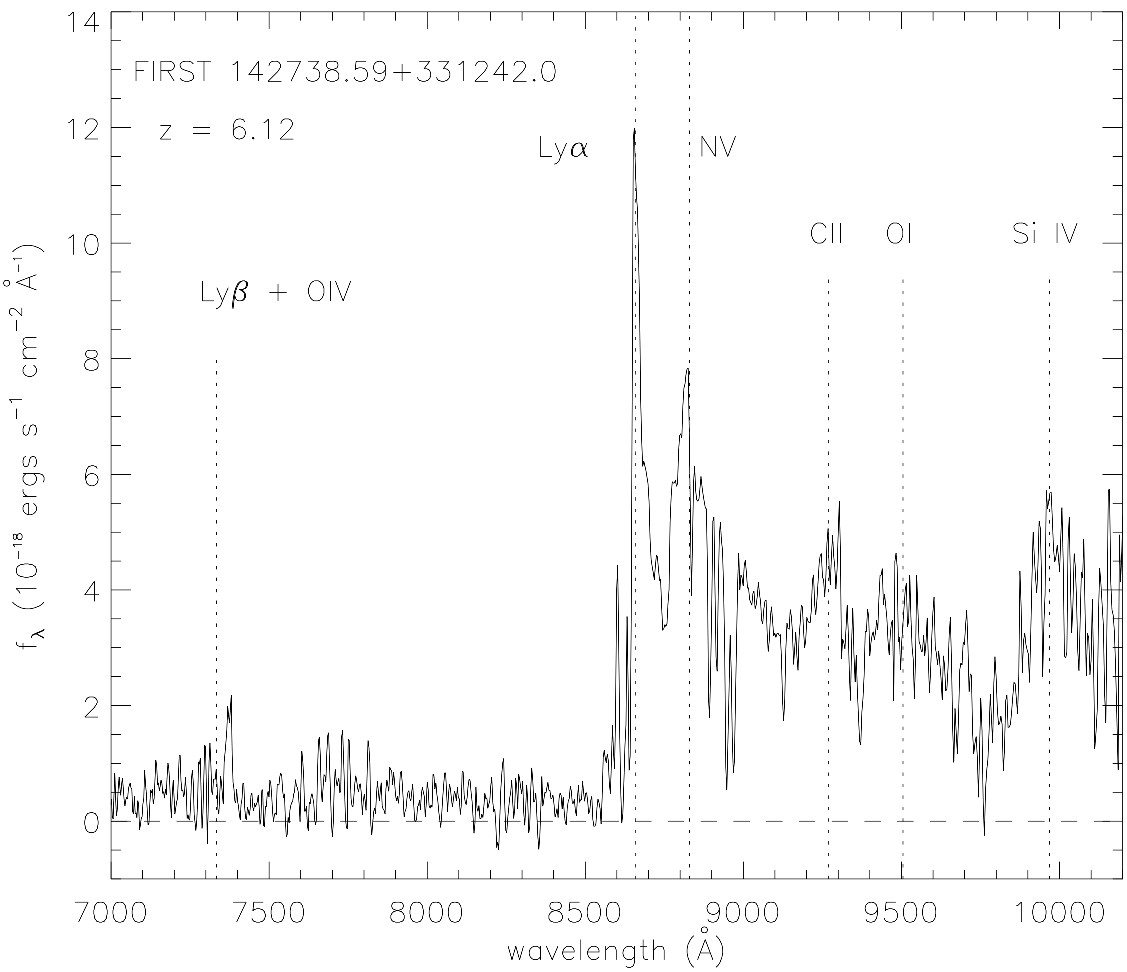

Fig. 1.— The spectrum of FIRST J1427385+331241 obtained on 2006 March 5 using the ESI spectrograph ($R \sim 4000$) on the Keck II telescope. Prominent emission lines are indicated with vertical dashed lines. Strong absorption features blueward of the N V and Si IV emission lines demonstrate that this is a BAL quasar.

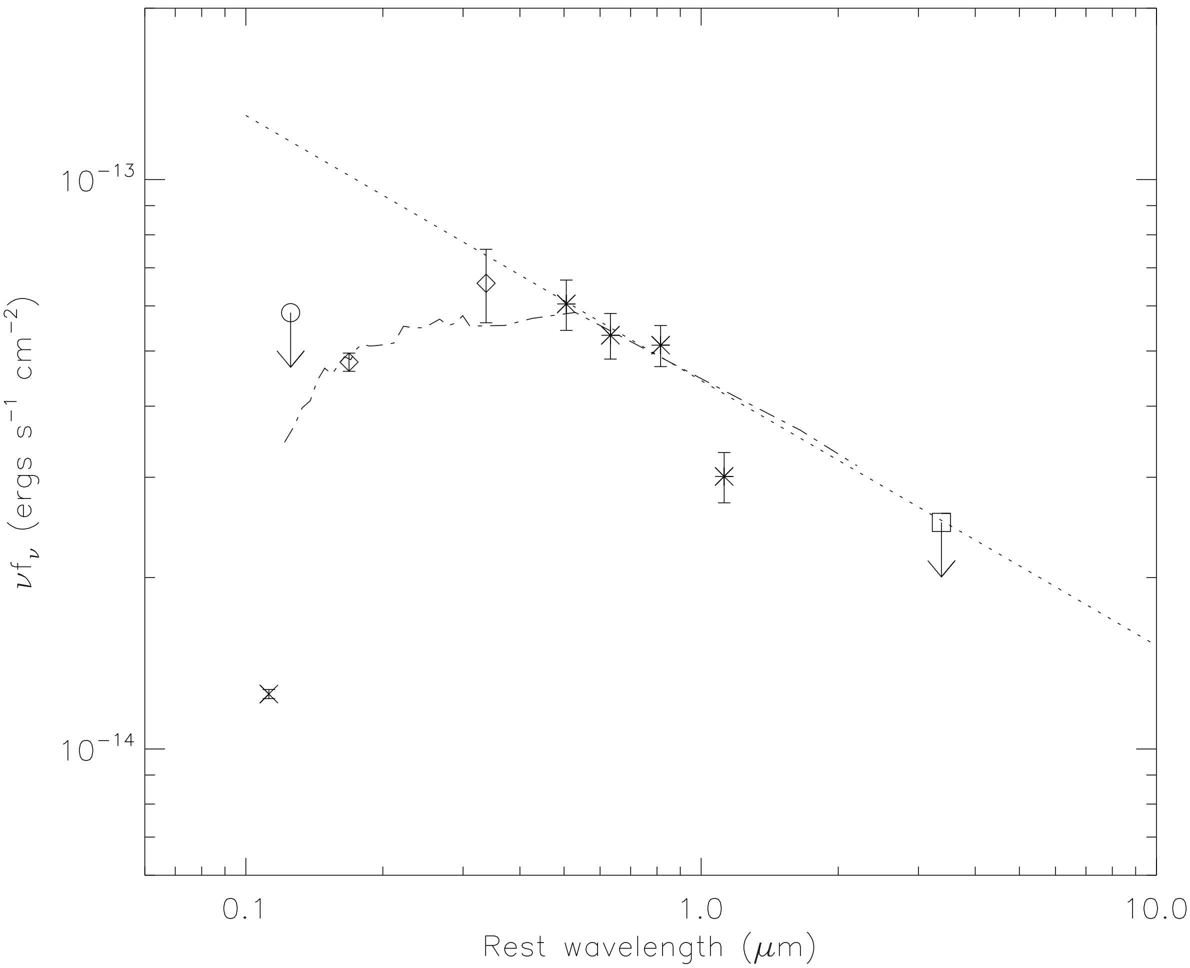

Fig. 2.— The rest-frame ultraviolet to infrared SED of FIRST J1427385+331241, compiled from multiple surveys. Points with error bars are: NDWFS I (cross), SDSS z' upper limit (circle), FLAMEX J,K_s (diamonds), IRAC $3, 4, 6, 8\mu$m (asterisks), and the MIPS 24μm upper limit (square). A representative power law with a slope of $\alpha = -0.5$ (dotted line) is fit to the IRAC $3-6\mu$m data and the MIPS 24μm upper limit. The steep drop in flux in the rest-frame ultraviolet suggests that the quasar is reddened by dust extinction. Shown in dot-dashed lines is a power law with slope $\alpha = -0.5$ extincted by SMC-like dust with $E(B-V) = 0.09$, using the values for SMC dust given in Prevot et al. (1984) and Pei (1992).

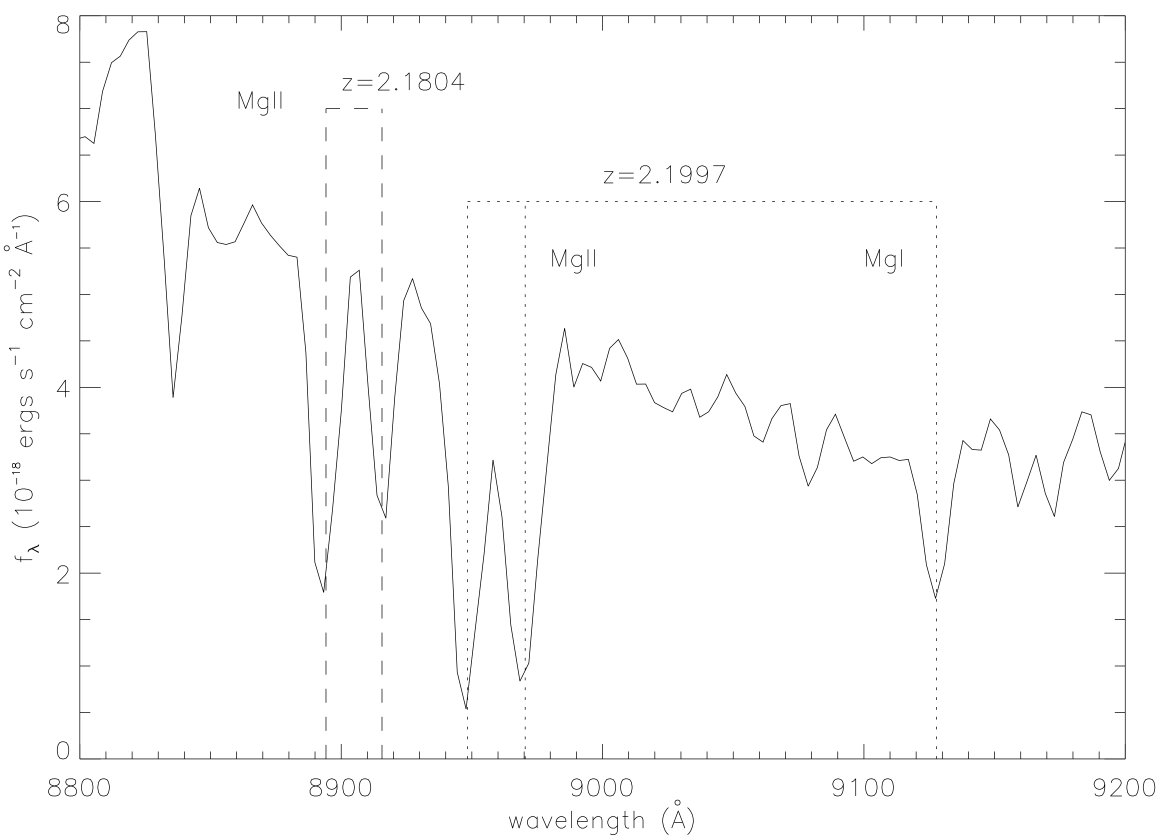

Fig. 3.— A portion of the Keck spectrum of FIRST J1427385+331241, revealing the presence of Mg absorption systems at $z_{abs,1} = 2.1804 \pm 0.0003$ and $z_{abs,2} = 2.1997 \pm 0.0003$. In both systems, the Mg II $\lambda\lambda 2796, 2803$ doublet is present, while the higher redshift system also shows the weaker Mg I $\lambda 2852$ line.

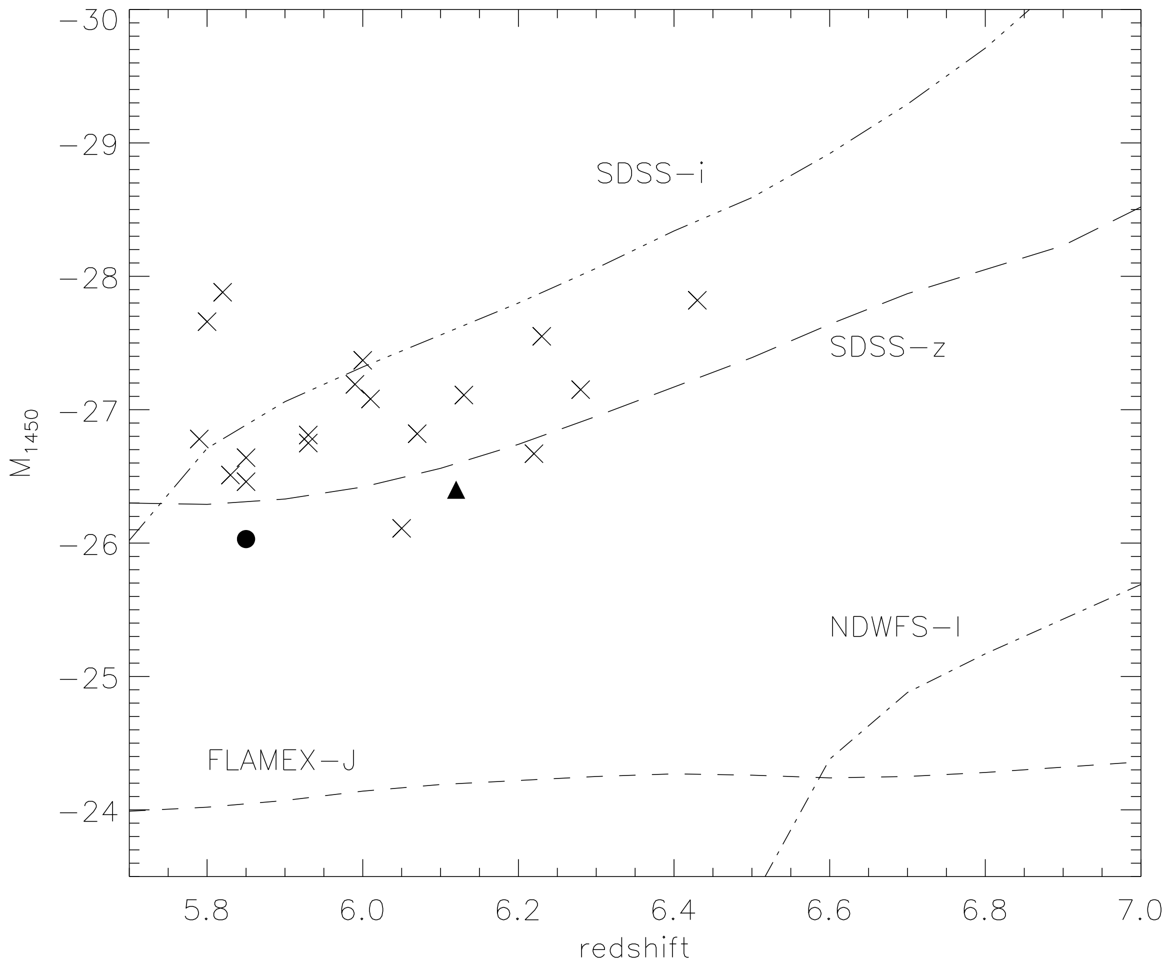

Fig. 4.— Detection limits of optical/IR photometric quasar searches obtained by redshifting the LBQS optical quasar template (Francis et al. 1991). The upper two lines show the limits of the SDSS i' photometry and the magnitude cutoff $z' < 20.2$ used for selection of quasar candidates by Fan et al. The lower two lines show the faintest luminosities reached by the NDWFS I and FLAMEX J photometry. Note that the NDWFS I band covers nearly the same wavelength range as the SDSS i' and z' bands combined. Published $z > 5.8$ SDSS quasars are shown with crosses. The $z = 5.85$ quasar found by Cool et al. (2006) using IRAC selection is shown as a filled circle. FIRST J1427385+331241 is shown as a filled triangle, showing that it is just below the nominal limit of the SDSS quasar search, but well above the NDWFS/FLAMEX detection limits. SDSS J1630+4012 ($z = 6.05$) is the faintest $z > 6$ quasar ($M_{1450} = -26.1$), yet it was an 8σ detection, $z' = 20.4$ (Fan et al. 2003). The inferred luminosity for FIRST J1427385+331241 is higher ($M_{1450} = -26.4$), but its red optical color put it below the SDSS z' detection limit.

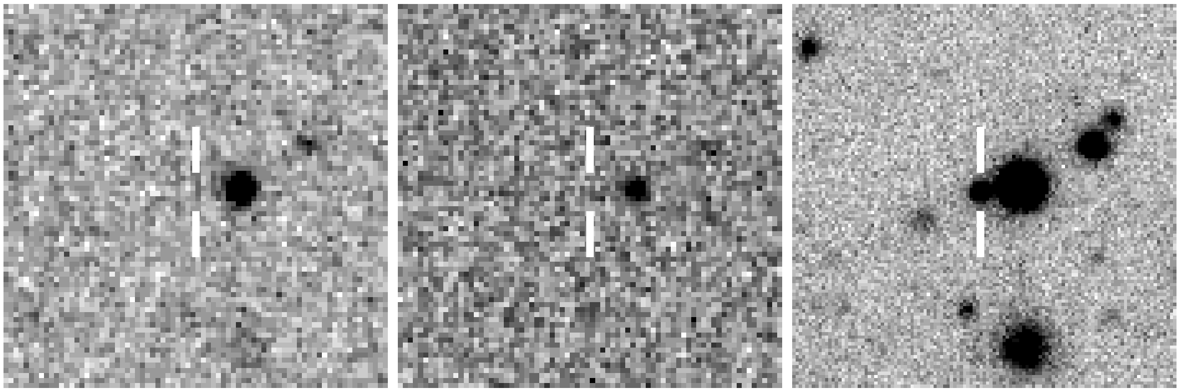

Fig. 5.— 30″ SDSS i', z', and NDWFS I cutout images of images of FIRST J1427+3312. The FIRST position is marked with vertical lines. A 3σ detection limit of $z' = 20.8$ is derived from examination of the SDSS images.

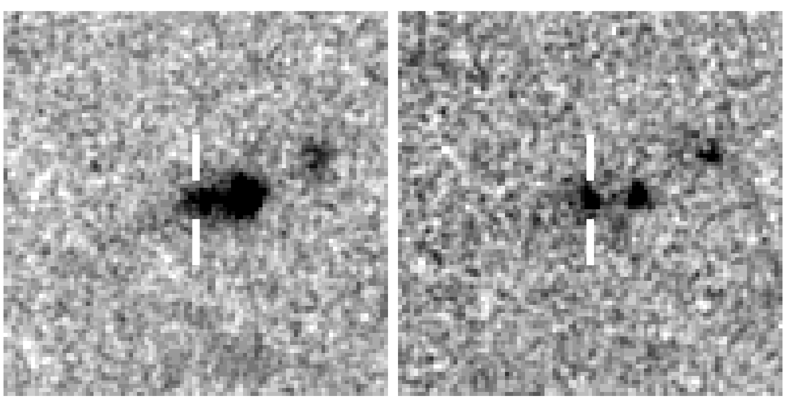

Fig. 6.— 30″ FLAMEX J and K_s cutout images of FIRST J1427385+331241, with the FIRST position marked by vertical lines. The source 3″ west has $J = 18.3$ and $K_s = 18.2$ in the FLAMEX catalog, while the quasar has $J = 18.7$ and $K_s = 17.4$. Using PSF-fitting to simultaneously fit both sources yielded $J = 19.7$ and $K_s = 17.9$ for the quasar.